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BIODYNAMIC AND SPASTICITY REDUCTION IN JOYSTICK CONTROL VIA FORCE REFLECTION

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FOR THE DIRECTOR

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When pilots are subjected to exogonous environmental influences such as complex acceleration fields during unusual aircraft maneuvers, these effects disturb the normal motion of the human body producing undesired biodynamic effects. These disturbances, in turn, affect how the pilot controls his aircraft. Thus, it becomes a problem of interest to investigate joystick controllers that show some resistance to these untoward effects. Force reflection algorithms, when applied to a joystick controller are shown to mitigate these unwanted motions induced by the environment. These same results also extrapolate to the problem involving the neuromotor disabled patients who suffer from spasticity. The disturbance in this case is internal, not external, but force reflecting stick controllers are shown to reduce these undesired responses. Data are given from pilots involving the external disturbances such as complex acceleration fields as well as for neuromotor disabled patients where disturbances are internally generated. Some general rules for applying these force reflection scenarios are given.

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PREFACE

In the early 1980s, a study of force reflection joysticks was initiated when an interesting phenomenon appeared as subjects performed during an experiment in a centrifuge motion simulator. This phenomenon occurred during an experiment investigating complex G forces and tracking when the accelerations (and net forces induced on the subjects) were in a direction negatively correlated with joystick movements. In the centrifuge simulator, the joystick motions were made in a lateral (side to side) direction and the controller was a displacement stick which had little resistance to movement. After observing, in the data, that a relationship existed between human tracking movements and the forces induced on the subject's arm, a fixed based simulator was constructed (the first prototype of the force reflecting joystick controller) which would replicate the same tracking task. In this test bed facility, however, an artificial force reflection was imposed on the stick to emulate the complex acceleration fields that were missing from the centrifuge experiment. Surprisingly, the same benefits afforded to the human tracking in the moving centrifuge also appeared in the fixed base simulator with the artificially induced force reflection.

For the next 10 years, a host of studies were conducted to better understand why certain types of force reflection algorithms used with joystick controllers were beneficial to human tracking. In the early 1990s, a very sophisticated force reflecting stick controller was built which could refine and further analyze this particular human-machine interaction.

These studies with centrifuge subjects had an analogy to a related problem in rehabilitation. The problem of mitigation of induced biodynamic effects produced externally by the environment on a pilot is analogous to another problem dealing with spasticity in patients with neuromotor disorders. Spasticity is another form of biodynamic disturbance but the source of the problem is internal to the subject and not external, as the issue is to the pilot flying the aircraft. At that time the Department of Veterans Affairs asked Armstrong Laboratory if such a force reflecting stick may enable patients in the VA system to obtain better control of displacement joysticks, which typically are the controller of choice on powered wheelchairs. An extensive study on spasticity was conducted which showed some alternative methods of generating force reflecting algorithms to reduce spasticity.

In summary, both problems have an equivalent basis. For pilots, the disturbance arises in the environment and is an exogenous influence, but it affects his tracking and how he flies his aircraft. Accordingly, for the patient who suffers from spasticity, the disturbance is internal, but can influence how a joystick controller is utilized. In both situations, a methodology is given in this report on how to mitigate these unwanted disturbances and provide better control of joystick input devices in either scenario.

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INTRODUCTION

In 1995, there is presently great interest in the development of controllers and manipulator systems which reflect forces to aid in perception, improving virtual reality scenarios, and to provide a human subject a better awareness of his environment through a "feel sense" at his hand controller. At the Armstrong Laboratory in early 1981, it was first recognized that there exists a certain synergy between forces that act on a joystick (that displaces) and the tracking task being studied. The forces induced on the first force reflecting stick were generated in a centrifuge motion simulator when pilots were tracking a lateral tracking task in a complex acceleration environment. This early experiment in the centrifuge motion simulator led to the development of force reflection joystick controllers at the Armstrong Laboratory.

There are many reasons why the addition of the appropriate force reflection algorithm to a displacement stick, in conjunction with his visual tracking scenario, should help or assist the human operator. In the classic book by Sheridan [1], he notes that the simple stimulus-response (S-R) reaction time measured when humans are given only visual information is approximately 160-180 milliseconds. The same S-R reaction time for a force pulse signal drops to 70 milliseconds. Thus for subjects, the force loop responds about 2 ½ times faster than the visual loop. This seems plausible because the visual loop has to traverse a path including the eye, the brain, and then to the hands or wherever the control action is to be actuated. The force loop may work in a faster manner through a shorter path, possibly including lower levels of brain function, or even possibly through a reflex arc to the spinal cord and back to the actuating member.

In any event, in the visual loop the longer processing time is certainly due to the visual system needing to sense and preprocess the stimulus and utilizing very high levels of brain function. Thus decisions about the nature of the visual stimulus require complex processing which adds substantial delay as compared to how force information is perceived. Hence, it is quite intuitive that the human force loop is a much more efficient method to process S-R data, if that is related to the task of interest.

The next step would be to try to combine the two sensory modalities (vision and force) in some productive manner to enhance the human in the performance of a task. Combining two sensory modalities, however, may not always help the human. In fact, it could deteriorate performance if the modalities are, in some sense, not compatible. In fact, Wickens [2] has proposed a theory whereas sharing sensory modalities has disadvantages when viewed within the context of a finite allocation resource model. Fortuitously from the early experiments in biodynamic disturbances of pilots flying aircraft to the later studies of spasticity with neuromotor disabled patients, the synergy between force and vision can be shown, in certain cases, to help one another if applied in an appropriate manner. Conversely, it is also very easy to demonstrate that the force-visual synergy can easily be destroyed if the force reflection profiles generated are not correctly coordinated with the visual scene.

This report discusses the types of force reflection algorithms that assist pilots in the type of tasks characterized as having biodynamic disturbances. It also describes what force reflection scenarios assist the neuromotor disabled patient. First an overall history of the development of force reflection at the Armstrong Laboratory, Wright-Patterson Air Force Base is given to raise a number of issues of how such a methodology may be helpful to assist humans in the performance of a tracking task.

The History of Force Reflection at Armstrong Laboratory

The first studies involving stick controllers and force reflection were initiated at Wright-Patterson Air Force Base in 1982 [3] when unusual data were observed from subjects making stick movements while riding in a centrifuge motion simulator. The subjects were required to move a displacement stick (which translates with little resistance) laterally (in a side-to-side motion) within an acceleration field that was changing in a direction consistent with the stick movements. The interesting results from that data showed that the subjects had an improvement in tracking performance when certain G fields were produced and, in particular, when these G fields had special alignment with respect to the stick movements. It was seen that force reflection (at the appropriate time and direction) could smooth out the subject's motion in controlling a stick controller even when exposed to external environmental influences. In addition, when a subject's hand was moved by the G forces in a direction not originally intended, the force reflection (opposing the direction of movement) would help dampen or reduce this untoward motion. This latter interaction was termed "Negative Biomechanical Feedthrough" [4] and it became apparent that the force reflection would not only smooth out the subject's response, but also could help the subject if exogenous sources of disturbance might interfere with his tracking. The references [5,6,7,8] documented the effect of the complex acceleration field interacting in a biodynamic manner with the resulting subject's performance that occurred.

It then seemed plausible that if such an interactive effect occurred in a complex acceleration environment, then it might possibly transpire on the ground in the absence of an external G field. To observe if improvement of tracking might occur when a subject was in a fixed base simulator using a displacement stick similar to that in the centrifuge study, the tracking task was reproduced on the ground. The stick, however, was then constructed such that it would reflect forces similar to those induced in the centrifuge when it rotated. This first prototype of a force reflecting stick (termed the "smart stick") was constructed using pneumatic actuators in the early 1980s. The results of the first experiment in a fixed base framework were surprising in that significant improvement still occurred in tracking performance utilizing the displacement stick and certain force reflection regimes. This led the investigation to questions like, "What type of force reflection can be used and for what specific applications?" A PhD candidate at Wright State University, Augustus Morris, worked on a dissertation topic related to answering some of the questions raised by the earlier studies. An extensive amount of analysis was conducted and published in [9] involving transfer functions, in [10] observing muscle changes with and without force reflection, and summarized in the PhD dissertation of A. Morris [11]. The main contribution of the dissertation was that certain force reflection regimes not only altered human performance, but also modified particular human muscle responses. Some muscle modeling was performed in this work and simple experiments with electromyographic signals (EMGs) were conducted on primitive arm motions involving human bicep and tricep muscles. The studies of EMG had to be planned carefully because as soon as a limb moves, most models of the human muscle system become invalid and break down. Extremely primitive arm motions were instituted and analyzed to reduce much of this possible artifact.

After studying data conducted on the experiments being simulated on the ground, various changes in strategies of how humans tracked were observed to occur [12] with and without force reflection and this led to interest in what manner may human muscles respond. In the earlier journal article [10], it was observed that patterns of muscle movements could be related to very primitive tracking or arm movements. In fact, one could discriminate if the force was on or off from data gleaned in special pattern recognition planes that were constructed to analyze human movement. A discussion of the modification of strategies was summarized in [12].

Theoretical investigations were also being initiated on specific optimum configurations of stick characteristics that might assist the human in the performance of a task. In [13], electronic circuit and mechanical impedance analogies were developed to model the human-machine interaction where certain types of optimization procedures may be utilized (e.g., maximize the power transfer to the environment subject to the human limitations and employing mechanical impedance models). Studies still continue in this area with respect to various biodynamic effects [14] that can occur in force fields with the human arm.

The data in [9] had also been run with different tasks or plants to be controlled. Evidence at that time strongly suggested that force reflection would work best in a type of tracking task termed "disturbance rejection" which will be defined in the sequel with block diagrams. This is akin to a pilot flying a helicopter with wind disturbances or turbulence directly entering the stick controller. The pilot is required to maintain a "status quo" situation in which he keeps the body axis of the air vehicle parallel to the earth. At low altitudes the helicopter would experience severe disturbances and the pilot must reject these unusual environmental effects. In [15] a study involving disturbance rejection was reported on the different tasks (plant dynamics or vehicle dynamics) and how certain force reflection regimes were beneficial to the tracking scenario. Air Force pilots were run in this experiment to investigate how force reflection reduced their "remnant" or portion of their stick response not directly correlated with the target tracking task. Certain matches and mismatches of the force reflection regime (in a real time sense) were shown to be beneficial to tracking. A rule of thumb (in the time domain) was given in [15] to design the force reflection regime in terms of any task or plant dynamics under certain restrictions.

One of the final studies conducted with the first prototype force reflecting stick involved two Master of Science thesis students at the Air Force Institute of Technology. Two captains participated in a six month effort which involved running subjects and various force reflection methodologies with a disturbance rejection task. Using fast fourier transforms (FFTs) and other methods of analyzing power spectra, the various signals within the loop were investigated as subjects tracked a task with and without force reflection. Part of the efforts of the research [16,17] was to look at information theory issues. Since the first prototype stick controller suffered from some nonlinearities, the FFT method of studying the problem did not demonstrate any great results from their presumed linearized analysis. It became apparent, at that time, that in order to investigate information theory aspects of force reflection and other precise studies involving human tracking, it would require a much more sophisticated test bed facility.

In 1991 a second prototype force reflecting stick controller [18] was built to improve on the technology in this area. The first prototype of this stick was a very large pneumatic device which, as mentioned previously, had some inherent nonlinearities and was operated by a relatively slow computer at that time (PDP-11). This made its response characteristics a possible confounding variable when used in precise studies. The new force reflecting stick was constructed to operate in two axes with a dedicated personal computer tasked to generate the tracking scenario and also maintain computer control of the force reflection paradigms to be run (both in time and in space). In this second prototype, permanent magnet DC electric torque motors were used to produce the force. This improved the linearity of the response as well as the response time. In addition, tests were made on various bandwidth characteristics of this new device after its construction. The force loop which provided the force reflection was able to change at 300 Hz or have an update rate of approximately 3 milliseconds for any change in force. This is sufficiently fast and well below any human detection threshold which eliminates any perceptual artifact. In addition, in the system constructed in [18], the visual monitor was updated at the rate of 66 times a second which is actually twice the rate in standard television. This visual scene given to the subjects was refreshed in a manner such as to not give any perceptual artifact in the visual loop. Thus both the force and visual loop had response characteristics sufficiently below human thresholds.

Simultaneously during this time, a number of Air Force patents and inventions were being developed to attempt to make this technology, funded by the Department of Defense (DoD), more available to the public. The first patent and invention [19, 20] addressed a force reflecting stick which had resistance to biomechanical disturbances as pilots flew aircraft in unusual acceleration maneuvers. The second patent [21] addressed issues related to stability and how a force reflection stick could stabilize a man-machine system in certain scenarios. This has applicability in flight control when problems such as pilot induced oscillation (PIO) may occur. This is the case of the human producing a large gain, or over correcting, and having to track his own error. Under conditions of time delays in display or stick response or in other situations, this leads to instability and the human induced oscillations may become larger and larger resulting in loss of control of the aircraft. A mathematical model to quantify how the stick's mechanical impedance may be modulated by a self contained stick controller was discussed in [22]. In [23] this concept was extended to accurate hand movement assistance whereas this methodology, for the first time, could be applied to people with a neuromotor disability (e.g., Parkinson's disease). In [24], this force reflection methodology was extended back to the flight control system problem by giving the pilot information in a tactile sense. This helps the pilot better perceive his external environment through a "stick-feel" scenario which needs to be coordinated with his visual scene (display or direct line of sight).

By the late 1980s, the use of force reflection was known at that time to mitigate subject biodynamic responses as well as reduce over control of subjects, particularly to disturbance rejection tasks. The Department of Veterans Affairs (VA) at that time became interested in this work as a means of reducing spastic responses when disabled patients have to control powered wheelchairs using displacement stick controllers. This type of research was discussed in [25] and led to a joint VA-DoD joint research effort [26]. The purpose of this effort was to utilize Air Force technology and transfer this knowledge into the health care sector. A host of other publications have been written on the results of this VA-DoD effort including the interpretation of an assistive aid (force reflecting stick controller) as an Intelligent Control System [27], viewing the acquisition of a target in terms of metrics or other parameters [28], studying the data from a phase plane perspective involving acceleration and velocity variables [29,30], and utilizing an information theory approach to describe the human-machine interaction to quantify how assistive systems of this type really help human performance [31] in a capacity sense. The PhD dissertation by T. L. Chelette [32] provided the fundamental data and initiated the first work of recognizing and identifying the difference between an intentionally commanded and an involuntary or spastic motion. The research by C. A. Phillips [29,30] has extended some of the methods of discerning the difference between a spasm and a voluntary quick movement. He uses a variety of phase plane diagrams incorporating different variables to look for particular patterns or characteristics of the tracking quantities.

To summarize how force reflection may help a human in the performance of a task:

(1) Force reflection works best in disturbance rejection tasks (cf. references [9,15]).

(2) For pilots, force reflection can stabilize their motion (e.g., PIOs cf. reference [21]).

(3) Force reflection may affect muscle behavior (cf. reference [10]).

(4) Strategies may change as a consequence of the use of force reflection (cf. [12]).

(5) More nonlinear force reflection, in a spatial regime, improves task performance which is based on minimum time movement [28,31,32].

(6) Parameters, metrics, and other characteristics of tracking are repeatable and predictable [28,29,30] with and without force reflection.

(7) There are theoretical reasons why force reflection can improve transfer of power/energy to the environment or improve biodynamic response [3,13,14].

Basic Definitions of the Human-Machine Problem

In defining an interaction of a human with his environment, it is necessary to characterize the two types of tracking tasks that may occur. In reality, every interaction involving humans with their surroundings is a combination of both of these types of tracking tasks. The first human-machine task interaction relates to target tracking.

The Target Tracking Task

Figure 1 illustrates the classic target tracking task involving human-machine systems. In this diagram, the human operator observes the error e(t) on the display. There are two types of error, pursuit and compensatory, but for this discussion, use will be made of pursuit error (both $f_T(t)$ and $\theta(t)$ are displayed separately) which is defined by:

$$e(t) = f_T(t) - \theta(t) \tag{1}$$

where e(t) is the pursuit error extrapolated from the display by the subject and illustrated in Figure 1, $f_T(t)$ is the target forcing function to be followed, and $\theta(t)$ represents the output of the system being controlled. The quantity P(s) in Figure 1 refers to the plant dynamics being tracked and $S_T(t)$ is the stick output.

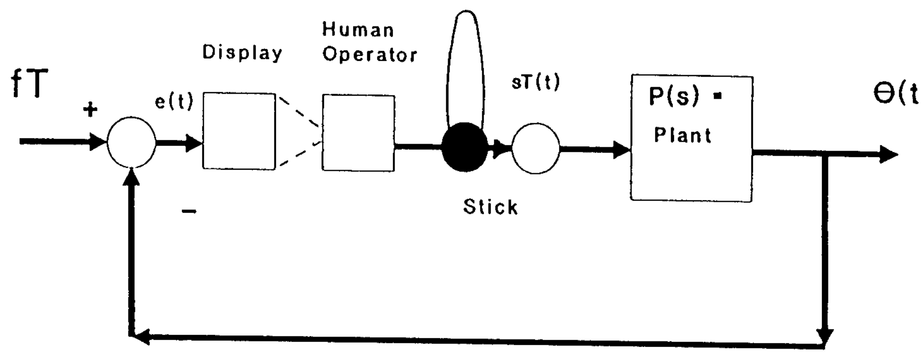

Figure 1. The Target Tracking Task

For the situation of a pilot flying an aircraft, $f_T(t)$ would represent an opponent aircraft in the sky which is being followed. For a landing scenario, $f_T(t)$ would represent the runway, or a flight plan illustrated on an Instrumented Landing System (ILS) display. $\theta(t)$ represents the heading angle of the plane under control by the pilot and P(s) is the aircraft dynamics.

An alternative way to view Figure 1 is in terms of driving a car on a road or, equivalently, driving a wheelchair on a specified path. In this situation, the variable $f_T(t)$ would represent the road the car has to follow, or the path the wheelchair has to traverse. $\theta(t)$ in this situation would represent the car position on the roadway, or the wheelchair heading position on a path and P(s) becomes the vehicle's dynamics.

Deviations of $\theta(t)$ from $f_T(t)$ induce a large error signal. For the aircraft, this simply means the heading angle of the pursuit aircraft simply does not follow the target $f_T(t)$. For the car or wheelchair control problem, large e(t) values imply the vehicle is off the intended course.

The second human-machine task interaction considered is related to disturbance rejection.

The Disturbance Rejection Task

Figure 2 illustrates the classic disturbance rejection tracking problem. In this situation, the human operator has the task of maintaining $\theta(t)$ to a zero (or constant) reference position. The mission of the human operator is to make stick movements $S_T(t)$ such that $e(t) \approx 0$ is regulated out. The input forcing function in this case is $f_D(t)$ which is an external or exogenous disturbance and is termed, "disturbance rejection."

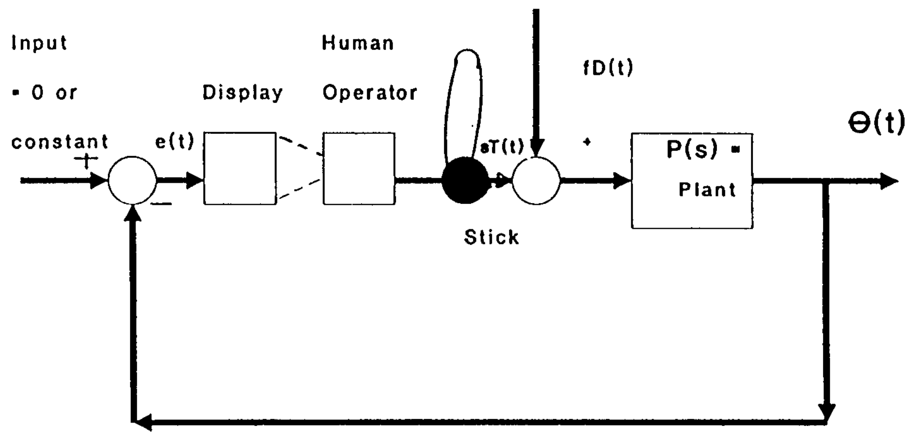

Figure 2. The Disturbance Rejection Task

An example of how this occurs in aircraft is best described by a helicopter pilot who has to maintain an even keel position of a helicopter when the vehicle is required to hover over a point close to the ground. In this situation, the wind turbulence is significant and the disturbance input becomes $f_D(t)$ which represents the wind turbulence affecting the helicopter blades. $\theta(t)$ is the orientation vector of the helicopter with respect to the earth. The pilot has to maintain the vector $\theta(t)$ parallel to the earth through the use of the stick commands $S_T(t)$ that he generates and P(s), in this situation, represents the dynamics of the helicopter.

The analogy of the disturbance rejection task to the car or wheelchair problem also has an interesting interpretation. If the car or wheelchair were to ride over a bump and this disturbance was transmitted to the vehicle displacing it off the path, the driver must make stick commands to maintain a level heading and preclude this disturbance from entering into or modifying how the vehicle maintains course.

In real situations, the human-machine interaction consists of a combination of both a target tracking task and a disturbance rejection task.

The Combined Target and Disturbance Tracking Task

Figure 3 illustrates a combination of both Figures 1 and 2 which depicts the combined target tracking scenario with the necessary disturbance rejection. This is typical of most tracking situations involving human-machine systems. It will be understood that Figure 3 is the system under consideration, although reference may be left out as to which forcing function is being considered as the primary effect.

There is one more feedback diagram which needs to be explained prior to describing the types of force reflection algorithms that are of use in mitigating undesired biodynamic response.

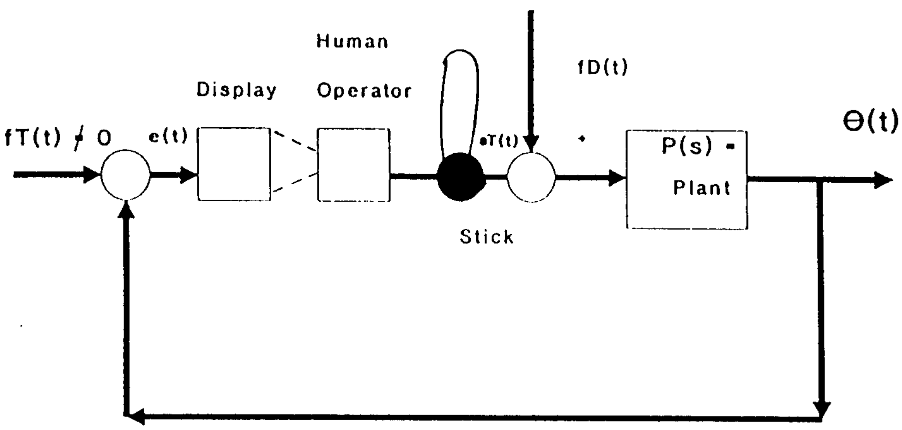

Figure 3. Combining Tracking and Disturbance Rejection

<u>Configuration of the Position-Force Loop Variables</u>

In order to implement force reflection with visual scenarios, a certain type of loop configuration will be required here. With reference to Figure 4, it is seen that our design requires the force loop being nestled inside the position loop. There are particular reasons for this type of configuration. First, from the prior discussion, it is known that the humans respond 2½ times faster with force information as compared to position information. Therefore, the loop action of the force variable must be made closest to the human. The position loop responds slower and, therefore, is updated at slower rates and is more isolated from the subject. It is also noted that in the force loop, information may be derived from feedback about the plant dynamics P(s) or possibly just the stick output. If the feedback loop depends only on stick output signals, then one can view this scenario as the modulation of the stick's mechanical impedance as the methodology to reflect forces. This may not be the best method to devise the appropriate force reflection algorithm.

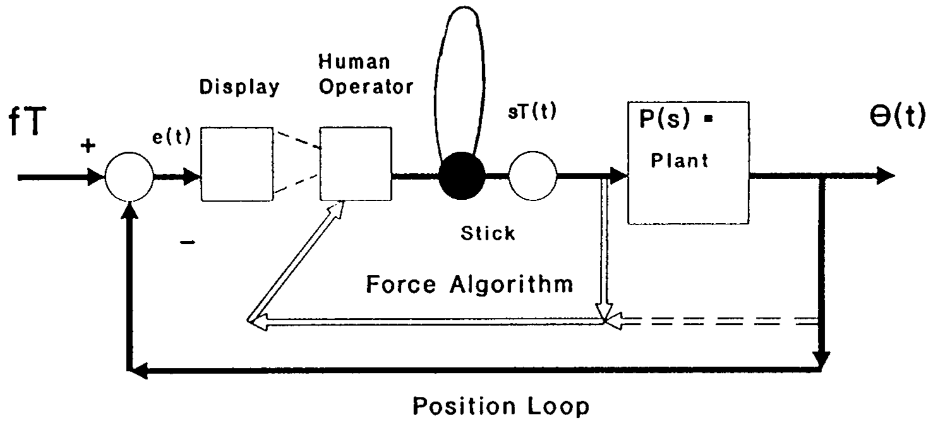

Figure 4. The Force - Position Loop Configuration

In any event, two experiments will now be presented. The first describes a time domain algorithm for the force reflection scenario. The second experiment has a spatial force reflection algorithm. The first method (time domain force reflection algorithm) is quite applicable for pilots who are exposed to disturbances caused by flying aircraft in complex acceleration fields.

Experiment 1 - Pilots and Biodynamic Disturbances

The experiment reported in this section was conducted [15] involving the first prototype force reflecting stick controller. Five Air Force personnel participated in the experiment and 12 experimental conditions were run to investigate different types of force reflection scenarios (in the time domain) that may help preclude human induced motion which is not productive in the performance of the tracking task. In interest of brevity, only the salient details of the experiment are described here; the interested reader is referred to [15] for a more detailed description.

Figure 5 illustrates the block diagram description of the experimental paradigm conducted in this first investigation. In a manner similar to Figure 4, the force loop is nestled inside the position loop, the human observes an error e(t) on the display, $f_T(t)$ represents the target tracking task, and $\theta(t)$ represents the plant output of $P_i(s)$. The difference between this diagram and that of Figure 4 is in the terms f_h which represents the force output of the human, f_R represents the reflected force from the stick controller, and the transfer function H(s) characterizes the mechanical impedance of the stick. The net force acting on the stick controller is defined as:

$$\text{Net Force On Stick} = f_h - f_R \qquad (2)$$

The displacement stick controller has a mechanical impedance (defined for this study as the ratio of position to force which, in actuality, is the first integral of the mechanical impedance) given by H(s) where, from (open loop) empirical measurements:

$$H(s) = \frac{4}{1 + s/5} = \frac{\text{Position}}{\text{Net Force}} \tag{3}$$

where s represents the Laplace transform variable. The goal in this experiment was to design the force reflection algorithm, denoted as:

$$\text{Force Reflection Algorithm} = K\, R_i(s) \tag{4}$$

subject to the plant dynamics $P_i(s)$ and the mechanical impedance of the stick given in equation (3) to produce enhanced performance for the human operator. Of particular interest is the relationship between the unknown $R_i(s)$ and the known variable $P_i(s)$ and any invariant relationship that may hold. Before any such a relationship can be given, it is necessary to define another loop variable of interest in this study. Let RB(s) be defined as the closed loop (force only) system which considers the stick response as the output and the human input force f_h as an input. Thus RB(s) can be defined by:

$$RB(s) = S_T(s) / F_h(s) \tag{5}$$

and represents the true response of the stick (with force reflection) from the perceived viewpoint of the human operator. Thus RB(s) represents how the stick feels to the human subject to both its inherent mechanical impedance and its force reflection algorithm imposed upon it. It is necessary to consider a concept termed "Extended Physiological Proprioception" [33],[34] which is the basis for the following definitions:

<u>Definitions</u>:

Matched Condition: $RB(s) = P_i(s)$ (6)

Mismatched Condition: $RB(s) \neq P_i(s)$ (7)

In other words, the matched condition occurs when the following transfer function relationships exist:

$$\frac{\text{Stick Position}}{\text{Human Force}} = \frac{\text{Plant Position}}{\text{Stick Position}} \tag{8}$$

or equivalently:

$$[S_T(s) / F_h(s)] = [\,\theta(s) / S_T(s)] \tag{9}$$

Table I illustrates the 12 different matched and mismatched conditions run with the Air Force pilots in this first experiment involving force reflection.

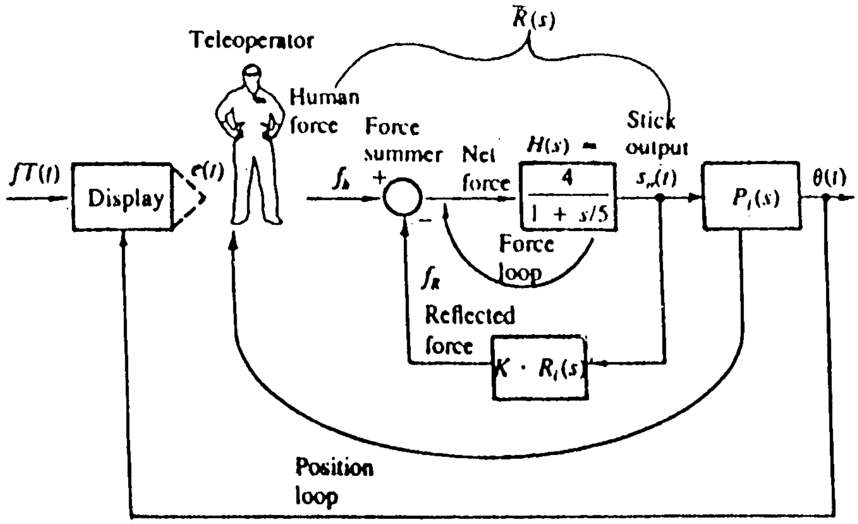

Figure 5. The Block Diagram for Experiment 1

Table I. Experimental Conditions Run- Experiment 1

Force Reflection $R_1(s) \neq RB(s)$	Matched or Mismatched With P(s)	Matched or Mismatched With P(s)	Matched or Mismatched With P(s)
No Force: $R_1(s)=0$	**Mismatched**	**Matched**	**Mismatched**
$R_1(s) = -s/30$	**Mismatched**	**Mismatched**	**Matched**
$R_1(s) = -0.8\ s$	**Mismatched**	**Mismatched**	**Mismatched**
$R_1(s) = -3.2\ s$	**Mismatched**	**Mismatched**	**Mismatched**

Data Collected From Experiment 1

The target input in this experiment was the sum of 15 sinusoids which is a deterministic input signal. Fast fourier transforms were used to determine power spectral density of the signals in the loop. Thus if signals were observed in the loop that were not in the frequency spectrum of the input forcing function, then they must be human generated. The performance of the subjects was measured by the root mean square tracking error which can be defined by:

$$e^2_{RMS}(t) = \sum_{I=1}^{N} (e_i(t_i))^2 / N \tag{10}$$

where N is the number of samples of one run (approximately one minute and sampled at 25 Hertz). Figure 6 illustrates the data plotted for two of the three different plant conditions ($P_i(s)$) versus three of the four different force reflection conditions. The three plants considered were:

Plants:

$$P_1(s) = 4/(1 + s) \tag{11}$$
$$P_2(s) = 4/(1 + s/5) \tag{12}$$
$$P_3(s) = 4/(1 + s/15) \tag{13}$$

These plants were selected based on characteristics of the bandwidth of the human and human-machine system which were known to exist in this experiment.

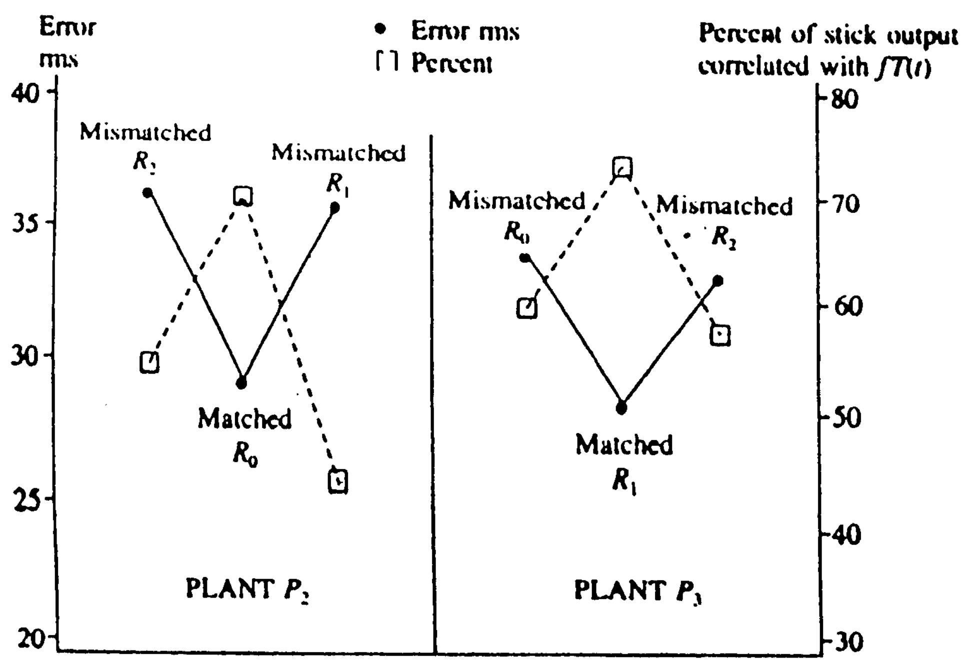

Figure 6. Empirical Data from Experiment 1

The data from the 5 subjects over the 12 conditions are displayed in Figure 6. The left most ordinate axis is the performance or error. The performance data are drawn in solid lines. On the right axes is the percent of the stick output ($S_T(t)$) correlated with the input target forcing function $f_T(t)$ and dotted lines in Figure 6 depict this variable plotted against the same independent variables. Early studies in the man-machine literature have defined the term, "remnant" as that portion of the human output not correlated with the input forcing function. In this context, a large percent of stick output correlated with $f_T(t)$ demonstrates a low remnant condition. To summarize the data from this experiment, it is noted:

(1) When the plant ($P_i(s)$) is matched to the closed loop stick force loop ($RB(s)$), then performance is enhanced, i.e., e_{RMS} is minimized.

(2) When the closed loop stick force loop is mismatched, the worst performance ensues in terms of e_{RMS} being maximized.

(3) When the plant is matched to the closed loop force loop characteristics, the percent of output of the stick is more highly correlated with the target forcing function. This means the human operator is utilizing his stick action in a more efficient manner.

(4) When the plant is mismatched to the closed loop force loop characteristics, the percent of remnant increases substantially, indicating the human is not very efficient in his utilization of the stick to track the error.

The result (4) may have an interpretation that the human is attempting to observe more about the system and generating remnant to achieve this goal. In actuality, he is experiencing confusion in what he "sees" and what he "feels" because the visual plant dynamics and the closed loop force dynamics are mismatched. To observe more about the loop characteristics, the subjects inject more energy into the signal $S_T(t)$ which is not correlated with the target forcing function. This improves their observation about loop dynamics, but reduces their effectiveness as a controller. Thus the human is more of an "observer" rather than a "controller" and must expend more energy to perform the task.

A second experiment will be illustrated to show how some methodologies can be used to mitigate a form of biodynamic disturbance that occurs with spastic patients. This type of biodynamic disturbance is internal to the subject, rather than external which is the case for the pilots and the first experiment.

Experiment 2 - The Spastic Problem

The second experiment discussed here involved 20 subjects (10 normal college students and 10 spastic patients). These subjects were being tested as part of the PhD dissertation of T. L. Chelette [32] and were of interest to the VA in a study on joysticks that may mitigate spasms.

The loop diagram describing the administration of the force and position variables is similar to Figure 4 except the task was now a discrete acquisition task designed to test how subjects would acquire a target in minimum time. Figure 7 illustrates the overall human-machine problem. It differs from Figure 5, mainly in the performance task displayed on the screen. Figure 8 provides a close-up view of the display given to the subjects. In this experiment, the second prototype stick controller was used and the stick output was the cross of width W2 as depicted in Figure 8. The target was the box of width W1 in the same figure. The objective was for the subject to get the cross into the box in minimum time which represents the acquisition of a target. Again, as with the first experiment, brevity will be the style in this report with only the salient details presented here. The interested reader can refer to [31] for a more complete description of this experiment. This study was also related to a classic performance paradigm used in psychology, termed, "Fitts' Law" [35]. In the early studies by Fitts, it was discovered that a speed-accuracy tradeoff occurs with human tracking, but no one had ever examined this scenario with force reflection. A second reason for running this experiment was that it represented only the acquisition aspect of another experiment that had looked at compensatory tracking. One can view a continuous tracking problem as composed of a number of discrete movements or acquisitions [36] and this was an underlying reason to study both spastic and normal human subjects in this experiment. A brief description of the spastic subjects run in this experiment is given as follows.

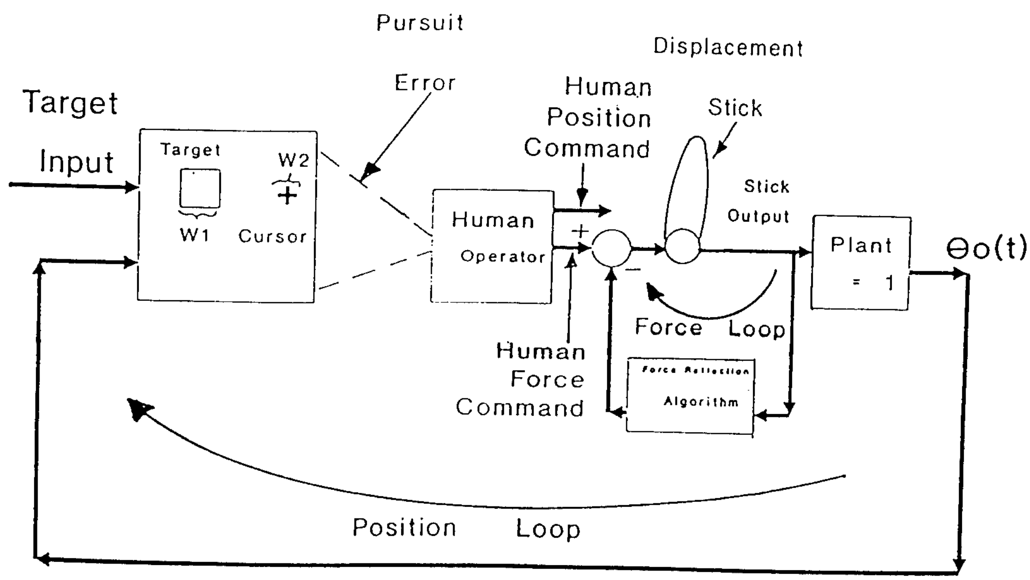

Figure 7. The Overall Man-Machine System (Experiment 2)

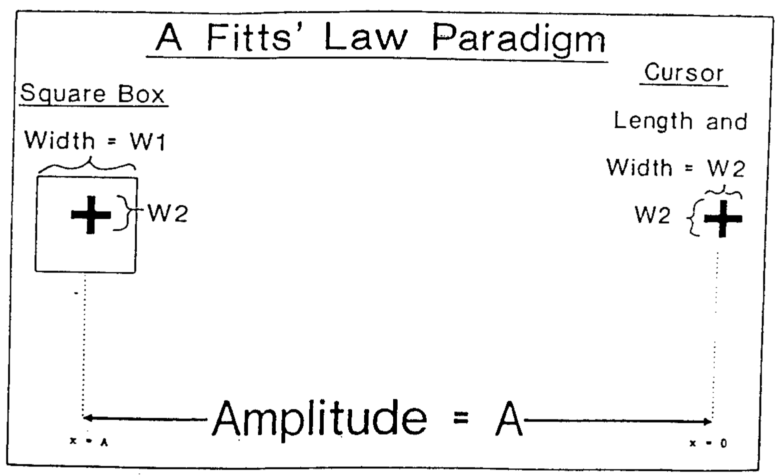

Figure 8. The Display Scenario (Experiment 2)

Characteristics of the Spastic Subjects

Ten subjects were recruited who were considered the equivalent of "operationally spastic." To attempt to define the term "spastic" provides wide controversy in the rehabilitation area, but our definition was based on operational characteristics. Of the 10 spastic subjects selected, 4 were head trauma injured, 4 were cerebral palsy, and 2 were stroke survivors. All 10 subjects had good eyesight and hearing, at least average intelligence, strength with the arm used to manipulate the stick, and had occasional spasms of the controlling arm. Table II illustrates the subject pool from the spastic subjects used in this experiment.

Table II. Spastic Subjects Used in Experiment 2

Subjects Initials	Age	Sex	Disability	Spastic Hand
KJW	10 Years	M	Head Trauma Injured	R
CEM	17 Years	M	Head Trauma Injured	R
DES	19 Years	M	Head Trauma Injured	R
IXR	22 Years	M	Cerebral Palsy	R
TED	22 Years	F	Cerebral Palsy	L
NAC	25 Years	F	Cerebral Palsy	R
WRS	24 Years	M	Head Trauma Injured	R
GNM	43 Years	M	Cerebral Palsy	R
TML	56 Years	M	Stroke Survivor	L
RAS	58 Years	M	Stroke Survivor	L

The 10 normals used as a control group were college students, civilian, and military personnel from Wright-Patterson Air Force Base. The force reflection algorithms employed were different from the first experiment and changed with respect to a space variable.

Force Reflection Conditions Used in Experiment 2

In order to better understand how the visual scene depicted on the TV monitor can be combined with force reflection algorithms, four such algorithms were developed in this study which depended on space, and not time as was accomplished in experiment 1. Figure 9 illustrates the four spatial force reflection algorithms employed in this study. They are stated as a function of x, the spatial variable depicted in Figures 8 and 9. The spatial force reflecting conditions are expressed in the following form:

Position Stick: $$f_1(x) = 0 \quad (14)$$

Linear Stick: $$f_2(x) = K_2\, x \quad (15)$$

Quadratic Stick: $$f_3(x) = K_3\, x^2 \quad (16)$$

Cubic Stick: $$f_4(x) = K_4 x^3 \quad (17)$$

It is also noted that the constants K_i, (i = 2,3,4) were selected such that at the boundary condition x = A, the following boundary condition is consistent for the three spatial force reflecting sticks:

$$f_2(A) = f_3(A) = f_4(A) = 5.5 \text{ pounds of force} \quad (18)$$

Thus the major difference between the sticks is in their spatial gradient of force with respect to distance and not on any relative magnitude values. The performance variable of interest to study the efficacy of the controllers in this study is now given.

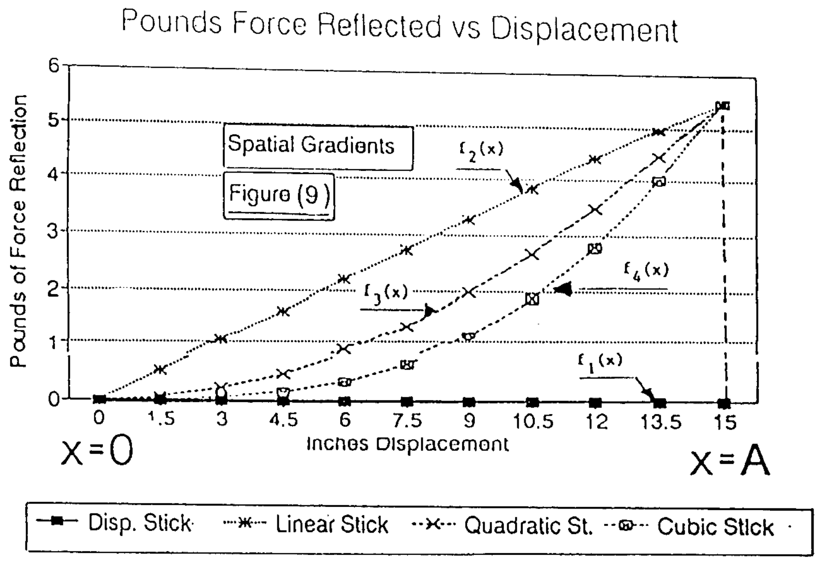

Figure 9. Spatial Force Reflection

The Performance Task Variables - Experiment 2

The subjects were instructed to place the cross (output of the stick) into the box in minimum time. Figure 10 illustrates data from this a typical Fitts law study for two of the normal subjects that participated in this experiment. The total time to complete the task is given on the ordinate axis. The independent variable is bits of task difficulty defined in the following manner:

$$\text{Bits of Difficulty} = \mathrm{Log}_2 \left[\frac{A}{(1/2)\,[W1 - W2]} \right] \quad (19)$$

where the variables A, W1 and W2 were defined in Figure 8.

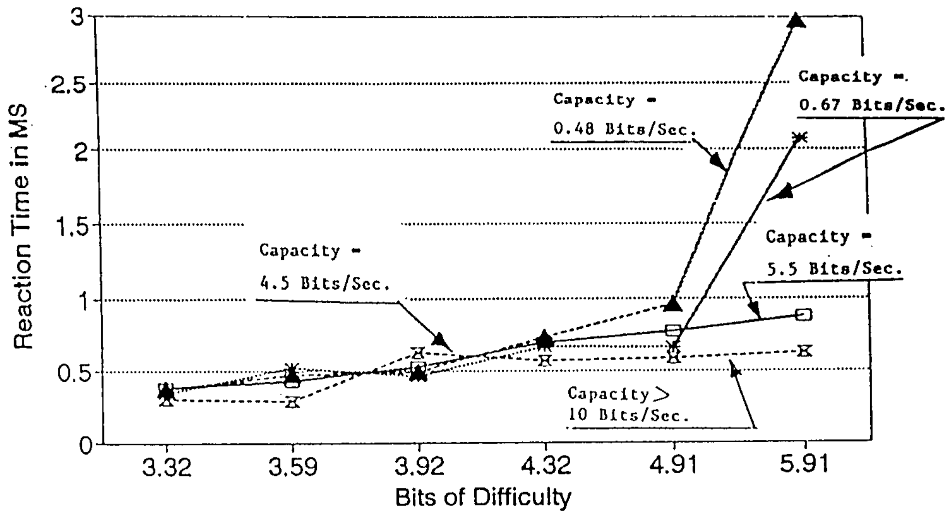

Figure 10. Two Normal Subjects With Typical Fitts' Law Curves

From the data displayed in Figure 10 it is seen that the effectiveness where force reflection has it most dominant capability is for the more difficult tasks (tasks with difficulty > 4.9 bits). Thus to truly distinguish the better force reflection conditions, estimates of information capacity were made on the last two tasks. To estimate information capacity (with units of bits/second), one needs to find the slope of the lines in Figure 10. The slopes of these lines have units of seconds/bit. The reciprocal slope of these lines has the units of bits/second which is consistent with the commonly used measure in information theory. The data are now presented across all the subjects, both spastics and normals.

Results from the Data Collected - Experiment 2

Figures 11 and 12 illustrate the information capacity plots averaged for all 10 normals and for the 10 spastic subjects run in this experiment for the two highest bit task difficulties. In comparing the two plots, one can make the following conclusions:

(1) For certain force reflection conditions, the spastics do as well or better than the normals (in terms of a capacity measure) for two of the force reflecting sticks versus the normals with the displacement stick.

(2) The percent increase in capacity of the cubic stick over the displacement stick, when normalized, is consistently 700% improvement, independent of whether the group was normals or spastics.

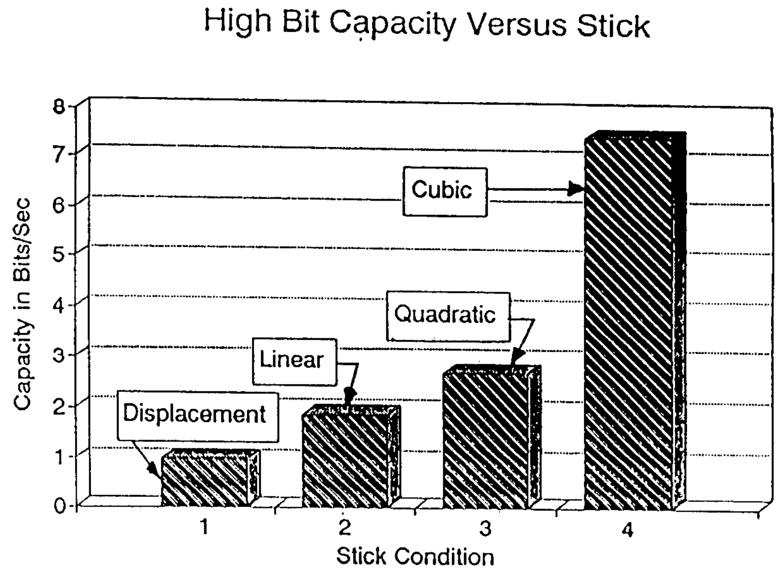

Figure 11. Average Capacity of Normals

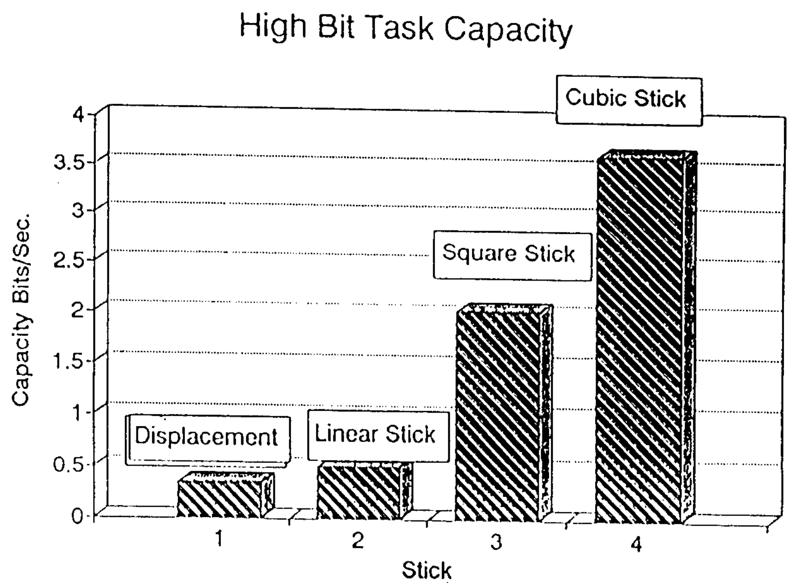

Figure 12. Average Capacity of Spastics

Space limitations preclude further discussion of this experiment so the interested reader is referred to reference [31] for a more detailed explanation. To summarize the results of the two experiments, the next section addresses a short, concise description of the knowledge learned at this point in time on force reflection.

Rules for Force Reflection - Pilots and Biodynamic Response

To summarize, briefly, how to apply force reflection algorithms in the time domain to help mitigate undesired response, the following procedure is illustrated:

Step 1: Given the plant dynamics $P_i(s)$ as illustrated in Figure 5, first obtain the mechanical impedance $H(s)$ (open loop) of the stick controller in the force loop.

Step 2: Next determine the closed loop transfer function of the force loop and determine $RB(s)$ subject to the mechanical impedance of the stick controller.

Step 3: The best force reflection condition is now given by the matched condition:

$$RB(s) = P_i(s) \tag{20}$$

and the feedback variable $R_i(s)$ in Figure 5 and equation 4 is chosen to make the matched condition given in equation 20 hold. Physically what this means is that the subject feels a transfer function in his hand characterized by $RB(s)$ and this matches, in a dynamic sense, the visual loop response (the relationship between the stick action and the plant response). Thus there is a "similar" causality between plant response and stick controller response. A brief summary of what works for spasticity and spatial force reflection is now presented.

Rules for Force Reflection - Spasticity Reduction

The results from experiment 2 suggest the following spatial force reflection scenarios which seem to assist human subjects in the study on rehabilitation.

Step 1: If the task is of the minimum time type, then the direction of the spatial force reflection must be in opposition to the direction of movement of the subject. This is a natural consequence of Newton's Second Law.

Step 2: The spatial force reflection scenario should be of the form:

$$f_i(x) = K_i\, x^n \tag{21}$$

where n should be as high a power as can be implemented. An extended discussion of this aspect of the problem is included in [31] and it is shown the human becomes more of a force control system in lieu of a position control system with the more nonlinear spatial algorithm. This is consistent with the previous discussion of why a force control system is 2-1/2 times more efficient than position control to perform a simple stimulus-response reaction task. Thus the algorithm in this case assists the human to process information more quickly and efficiently.

There are many new directions of this research and some of the topics presently being pursued are now given.

Future Directions of this Research

This report has discussed just two aspects of this problem and addressed certain scenarios in which time, or spatial force reflection may be used to mitigate unwanted or undesired biodynamic response. Other topics of interest to be studied include, but are not limited to:

(1) The studies so far have considered mainly normal forces to the human body. There is a vast, unexplored area concerning tangential or shear forces that affect humans in their perception. This includes textures and a host of other perceptions that may assist in the performance of difficult and highly accurate tasks.

(2) There are issues of energy that need to explored. One can view the force field as a "sink of energy" which is absorbing unwanted or unnecessary energy from a human-machine interaction that is undesirable. There are many methods to approach this problem designing the force field such that it takes "unwanted" or "undesirable" energy out of the human-machine interaction which are counter productive to the performance of a specified task. "Good" and "Bad" energy can be defined and may be interchanged with each other.

SUMMARY AND CONCLUSIONS

Two experiments are presented to illustrate how to devise force reflection algorithms in joystick controllers to mitigate unwanted or undesired biodynamic response. The first method is based in the time domain and shows how to wrap feedback loops about force control sticks to provide better coordination between the "feel" information the operator senses and the "visual" information he observes. The second experiment was designed in the spatial force reflection regime and illustrates some ways to improve how a human responds in tasks related to acquisition or minimum time movement tasks. Extensions of this research are also given into several other methods to explore how to define force reflection algorithms for other tasks and problems.

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